International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)
ISSN(P): 2249-6890; ISSN(E): 2249-8001
Vol. 8, Issue 6, Dec 2018, 289-302

MECHANICAL CHARACTERIZATION OF DEFORMED AND HEAT TREATED COPPER-EUTECTOID STEEL POWDER REINFORCED COMPOSITES

GOWRI SHANKAR. M. C, SATHYASHANKARA SHARMA, KARTHIK. B. M*, ANUSH. D PINJAR, NOEL JOSE & HITHESH CHANDRAKANTH SHRIYAN

Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal, India

ABSTRACT

Copper is well known for its formability, conductivity and corrosion resistance properties. The property of pure copper cannot be altered. There is provision in metal family to alter its property by alloying or subjecting to intentional cold deformation. The reinforcement addition introduces miss fit strain in the copper matrix due to the difference in the coefficient of thermal expansion of matrix and reinforcement, the property of copper as a whole is altered. The reinforcement phase alteration by heat treatment changes the room temperature structure of reinforcement, the expansion or contraction of the reinforcement takes place in the matrix, according to the packing efficiency of the room temperature structures formed by heat treatment. Since reinforcement addition may not affect unit cell property of copper, an attempt is made here to reinforce heat treatable ferrous material into the copper matrix. To study the work hardening effect on copper and its composites, cold rolling is also performed to see the extent of property enhancement (hardness). To analyze the dispersion of reinforcements in the matrix, the behavior of reinforcements during tensile fracture and the effect of deformation & rate of cooling on the grain, metallography is also employed. It is expected to improve the hardness and tensile strength of copper considerably with the small addition of reinforcements. Work hardening effect of copper may be enhanced by introducing reinforcements with and without heat treatment, so that the specific weight of copper is substantially improved.

***KEYWORDS:** Matrix, Hardness, Strength, Stir Casting & Cold Rolling*

Received: Aug 24, 2018; **Accepted:** Sep 14, 2018; **Published:** Nov 01, 2018; **Paper Id.:** IJMPERDDEC201833

Original Article

1. INTRODUCTION

The metal copper is extracted from the earth and is requisite for the development of all life forms, and has been vital in the evolution of civilization, contributing to both social as well as technological development. The valuable properties of copper that were evident at the dawn of civilization were its attractive colour, excellent ductility and malleability, and work hardening capability. In modern ages, further properties have been appreciated and exploited for applications like high thermal and electrical conductivities, corrosion and biofouling resistance and antimicrobial properties. Today, copper and its alloys contribute significantly in the development of renewable energy, information technology, architecture, health and sanitation [1]. Steel is an alloy of iron and carbon and other elements. Because of its high tensile strength and low cost, it is a major component used in buildings, infrastructure, tools, ships, automobiles, machines, appliances, and weapons. There are different types of heat treating processes for steel. The most common treatments are annealing, quenching and tempering. Carbon steels are categorized into three groups depending on their carbon content they are low carbon steel, medium carbon steel

and high carbon steel. Steel with 0.8 wt. % carbon is very hard in general useful grades of carbon steel family. Non heat treatable copper can be converted into heat treatable by the addition of heat treatable reinforcement, so that property of matrix metal will be changed with respect to heat treatment variable.

Copper and its alloys are widely used in many application like building industry, electronic products, industrial machinery, consumer products and transportation. There are more than 300 commercially used compositions of copper alloys, some alloy of copper like C106/CW024A are widely used. The world consumption of copper and its alloy is around 20 tons per annum. This huge demand of copper globally is luckily helped by one property of copper, that is, recyclability; more than 40% of global copper consumption comes from recycled copper. Copper alloys also have excellent anti-microbial properties and has the ability to kill 99.9% bacteria [2-5].

The properties of the composite can be further increased by processes like deforming. Since copper has got FCC structure, can be easily be deformed [6]. Copper composites may be worked at different temperatures at different deflection rates. In these processes, metals are plastically deformed above their recrystallization temperature, thus being above the recrystallization temperature allows the material to recrystallize giving rise to new set of improved properties.

Strain hardening, also known as work hardening is the process of improving properties of a metal or composite by plastic deformation. This strengthening occurs because of dislocation movements and dislocation generation within the crystal structure of the material [6-10]. Composites are not amenable to heat treatment, including low-carbon steel, are often work-hardened. Copper is usually strain hardened because of its comparatively larger melting point.

Many research works have been carried out to improve properties, especially hardness, machinability and strength in copper alloys by the addition of a number of reinforcements like fly ash, SiC, B_4C etc. Here, attempt is made to alter the properties of non-heat treatable pure metal (Cu) by reinforcing heat treatable eutectoid steel powder. By controlling the process variables, property alteration of pure copper may be attempted as per the application.

2. LITERATURE REVIEW

The copper-eutectoid steel composite responds positively for heat treatment, to enhance tensile and hardness properties. Literature survey shows that, “there is decrease in the porous level, increase in corrosion resistance as amount of wt. percentage of reinforcements (eutectoid steel powder) added to copper is increased [11]. Cold rolling was done to reduce volume defects such as voids, blow holes and pores that may have developed during casting. Literature results show that there is 22% improvement in hardness related properties and 30% improvement in tensile strength, if copper is reinforced with harder reinforcements [12]. Literature also shows no evidence for the reinforcement of eutectoid steel powder. In view of this, it is decided to reinforce eutectoid steel powder into copper matrix.

Kenneth Kanayo Alaneme et al. [11] studied on the mechanical properties, wear behavior of copper matrix composites reinforced with steel machining chips. Steel machining chips with chip size range of 105 micrometer and below were utilized and the copper matrix was prepared using stir casting. The amount of chips taken for experiment was 5, 7.5 and 10% in the total composition. The samples were subjected to heat treatment and cold rolling. Optical microscopy was used to examine the microstructure. The wear behavior of the composites examined using a rotary platform abrasion tester. The mechanical properties of the composite was calculated using an Universal testing machine(UTM) for properties like tensile strength, and Rockwell Hardness of ‘C’ scale was used to check hardness. After the experiments, it was observed that the addition of steel machining chips improved the tensile strength, hardness and wear resistance (maximum

for 10% of steel machining chips). Thus, it can be concluded that steel machining chips is a suitable reinforcement for producing copper matrix composites.

Harish et al. [12] studied on mechanical properties copper-TiC metal matrix composite. The copper and its composite are prepared using the stir casting technique at 1100°C, in which 10 wt. % of particulates were dispersed in the base matrix. Hardness result has shown a maximum of 22% improvement in hardness of composite when compared with unreinforced matrix metal. A maximum increase of 30% in the tensile strength values were observed in Cu-TiC composite compared with the pure copper.

Donka Angelova et al. [2] presented on monitoring the mechanical characteristics of rolled electrolytic copper. High-Electrical-Conductivity (ETP) copper produced in soft, half hard and hard temper of 0.70 mm thickness, accordingly to the European Standard EN 13599 Copper plate, sheet and strip for electrical purposes were brought and mechanical properties were noted. ETP copper product in soft temper was prepared by hot rolling, cold rolling and annealing at 680°C. ETP copper product in half hard temper was prepared by hot rolling, cold rolling and annealing at 650°C, additional 12% deformation was given to obtain specimen of required thickness. ETP copper product in hard temper was prepared by hot rolling, cold rolling and annealing at 650°C, additional 18% deformation was given to obtain specimen of required thickness". Results show that thermo-mechanically treated copper in hard temper has highest tensile strength and lowest plasticity compared to other two tempers.

Summarizing all the literature papers referred, it is found that as the percentage of reinforcement added to matrix increases, the tensile strength and hardness increases up to certain weight percent, further addition of reinforcements decreases the properties [11-16]. It was revealed that the hardness and ultimate shear strength of the conventional annealed specimen decreased and elongated, and the impact toughness increased [17-18]. Addition of steel machining chips improved the tensile strength and hardness [11]. Copper in hard temper has highest tensile strength and lowest plasticity.

3. METHODOLOGY

For the present study, copper-eutectoid steel powder composites are fabricated using two-step stir casting method. The prepared castings are machined to prepare the specimens for microstructure, hardness and tensile tests. The specimens are heat treated for precipitation hardening at peak aged conditions. The specimens both as cast and heat treated will be subjected to the above tests.

3.1 Preparation of Copper-Eutectoid Steel Powder Composite by Stir Casting

The fabrication of the composites was carried out in liquid metallurgy route via step stir casting technique. The copper billets were introduced into the crucible and the temperature of the crucible was raised to 1150°C [9]. The impurities i.e. in the form of slag were skimmed out. After slag removal, eutectoid steel powder of purified scrap of particulate ranging from 50-70μm which was preheated to 105°C [9] for 1hr, was introduced into the vortex of the molten metal after the attachment of the stirrer. The stirrer was set to the desired rpm for the formation of the vortex, which is a basic requirement for uniform distribution of the powder. During the addition of the powder, the melt was maintained in liquid state at temperature ranging from 1100 to 1150°C for better solubility of eutectoid steel powder in the molten metal. This was followed by manual stirring for 5 minutes. The molten composite was poured into the preheated moulds which were maintained at 350°C. 2 wt.% of eutectoid steel powder were added and resulting specimen with 2 wt.% of eutectoid

steel powder were obtained.

The castings were machined to prepare the specimens for conducting experiments. Figures3.1, 3.2, 3.3 and 3.4 show the step by step procedure to obtain the cast composite by stir casting.

Figure 3.1: Copper Billets

Figure 3.2: Pre Heating of Eutectoid Steel Powder

Figure 3.3: Melting Copper

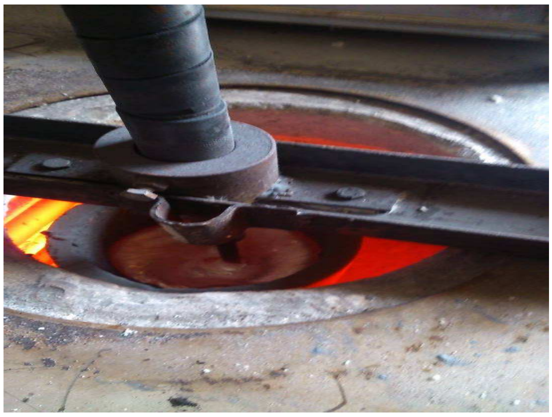

Figure 3.4: Stir Casting of Copper-Eutectoid Steel Composite

Figure 3.5: Castings of Copper-Eutectoid Steel Composite

Figure 3.6: Specimens for Tensile, Microstructure, Hardness and Cold Rolling Tests

Figures 3.5 and 3.6 show the castings of copper-eutectoid steel composites and standard test specimens.

3.2 Heat Treatment

Annealing: The hardness and tensile test specimens are heated in furnace to 750°C and held for 2 hours followed by furnace cooling. Normalizing: The hardness and tensile test specimens are heated in furnace to 750°C and held for 2 hours followed by air cooling.

3.3 Cold Rolling

Cold rolling is carried out for copper and its composites, in as-cast condition using 2-high rolling mill with initial specimen thickness of 10 mm. The cold rolling mill is shown in figure 3.7**.** The chosen specimens were cold rolled at different deformation densities of 10, 20 and 30% and are sent for hardness test.

Figure 3.7: Cold Rolling Mill

3.4 Hardness Measurements

Hardness tests are carried out for copper and its composites in as-cast, heat treated and cold rolled condtion (ASTM E10-00), using Vicker's hardness testing machine with diamond indenter and 100 gf load at dwell time of 15 s for each specimen (Matsuzawa digital micro hardness tester, Model: MMT-X7A). The Vicker's hardness testing machine is shown in figure 3.8**.** In order to eliminate possible segregation effect, the average of a minimum of five near identical indentation readings are noted down for each specimen at different locations of the test samples.

Figure 3.8: Vicker's Hardness Testing Machine

3.5 Tensile Test of Copper and Its Composites

Tensile properties explain how the material will react to forces being applied in tension. Tensile specimen is prepared according to ASTM-E8M standards as shown in figure 3.10. Circular cross section specimen with 6.41 mm diameter and 22.70 mm gauge length is prepared. Tensile test is carried out on electronic tensometer (Figure 3.10).

Diameter of specimen is measured using Vernier Caliper and cross sectional area is calculated. The load cell value is kept to 20.5 kN and test mode is selected as break. The cross head speed is kept constant at 10 mm/ min, with length increment value of 0.01 mm. The as-cast specimen is fixed firmly in gripper and load is applied.

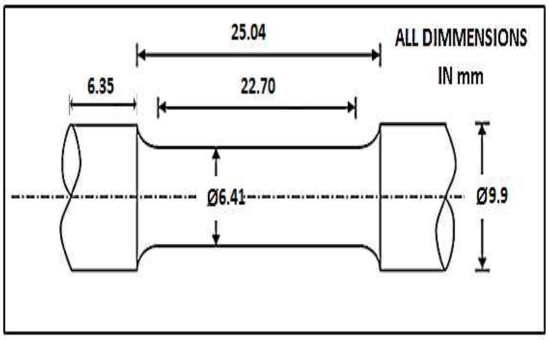

Figure 3.9: Tensile Specimen (ASTM-E8M) [19] (All dimensions are in mm)

Figure 3.10: Electronic Tensometer for Tensile Test

4. RESULTS AND DISCUSSIONS

The results of the conducted tests are recorded in the form of tables and graphs. Hardness test is carried out to study the effect of reinforcement on the matrix for indentation resistance. Tensile test is conducted to find out the ultimate tensile strength of the specimen.

4.1 Microstructure Analysis

In as-cast condition, the microstructure shows equiaxial grains with a lot of dendrites. Thicker grain boundary indicates the directional solidification of the casting. Some regions grain clusters are also observed. This implies the excellent purity level of the copper metal showing homogeneous solidification. The clustered grains (bigger in size) are generally observed at inner region of the casting. At the surface, some porosities are also observed. Subsurface grains in the casting appear to be finer compared to inner region. This is due to the higher cooling rate of the casting nearer to the surface as well along the interface of melt and mould. The deformed (rolled) grains are elongated in the direction of

working. Some seems to be perfectly aligned in the direction of working, some shows mixed orientations and some are twisted at an angle to the direction of working.

Pure copper: Pure casting at 500X is observed (Figure 4.1) with a lot of dendrites usually along the grain boundary shown as finer dots, ovals & polygons. Grains nearer to & at the surface seems to be finer as compound to in depth grains. Some grain clustering is also observed in pure metals. Thicker grain boundaries are seen as big as grain itself with a number of finer dendrites. Between the dendrites some porosities are also observed and these porosities are not observed within the grains.

The deformed specimens in Figure 4.2 shows elongated grains in the direction of working (rolling). There is no much differences observed in the dendrites and porosities in SEM images. Cu-1% Fe powder composite: As cast structure shows equiaxial & clustered grains at lower magnification (Figure 4.3). Higher magnification at 1000X shows lesser dendrites (Figure 4.4). Even though equiaxial, some slight modifications in the grains (slightly stretched) is also observed. This may be due to the complexity occurred during faster cooling rate of the casting coupled with more members of nucleation sites [19]. At very high magnification, lesser porosity and lesser dendrites are observed (Figure 4.4). This lesser porosity & dendrites are due to the more number of nucleation sites for phase transformation [20].

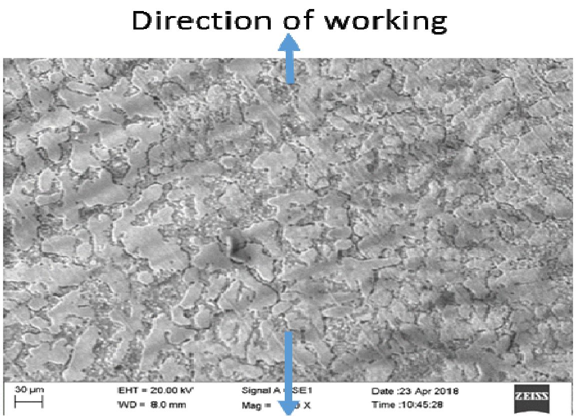

Figure 4.1: Pure Cu as-Cast 500X

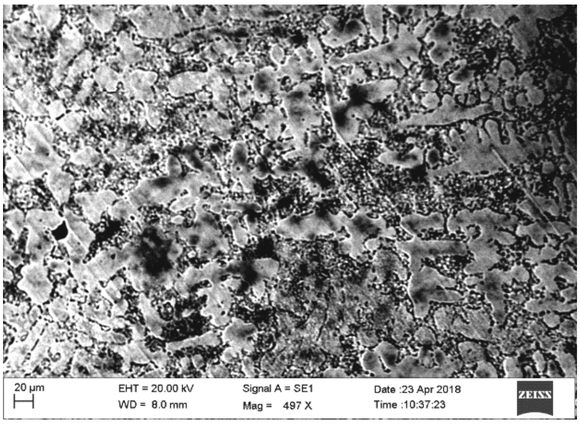

Figure 4.2: Pure Cu 20%D -500X

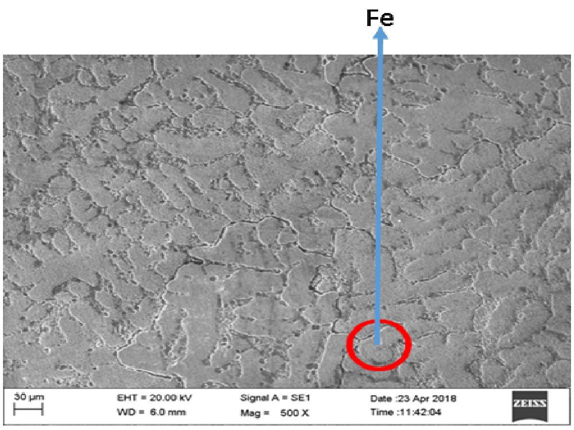

Figure 4.3: Cu-1% Steel as-Cast-500X

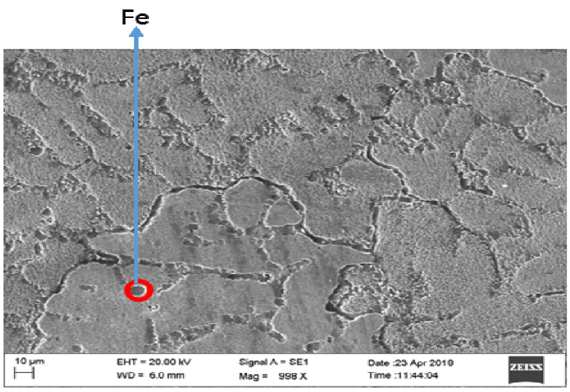

Figure 4.4: Cu-1% Steel as-Cast-1000X

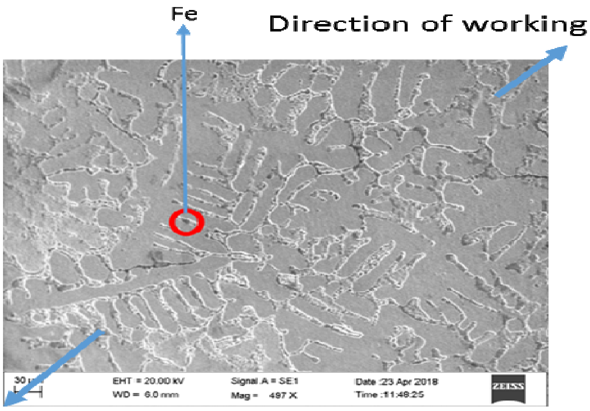

Figure 4.5: Cu-1% Steel 20%D-500X

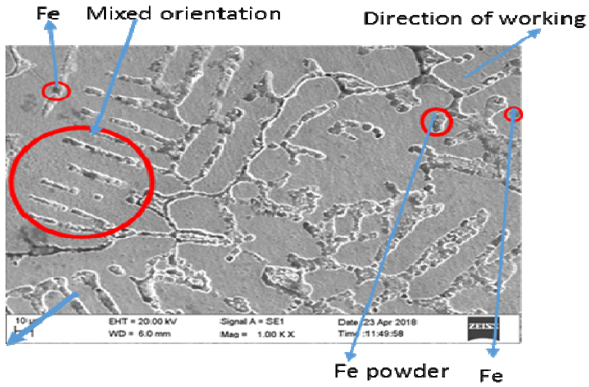

Figure 4.6: Cu-1% Steel 20%D-1000X

In the rolled condition, at all magnifications the microstructure shows elongated grains in the direction of working (Figsure 4.5 & 4.6). Some regions mixed direction oriented grains are also observed. This may be due to the improper handling of the specimen during rolling.

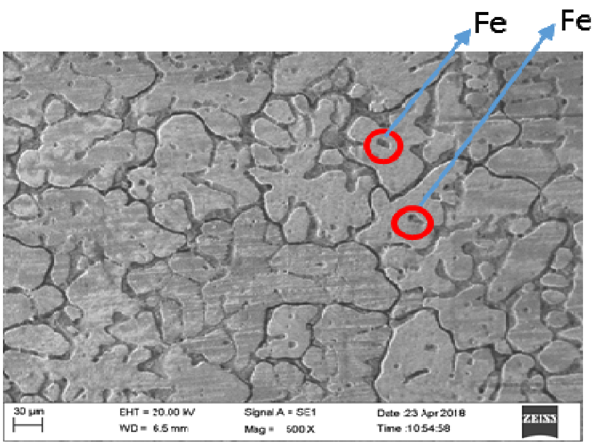

Figure 4.7 Cu-2% Steel as-Cast-500X

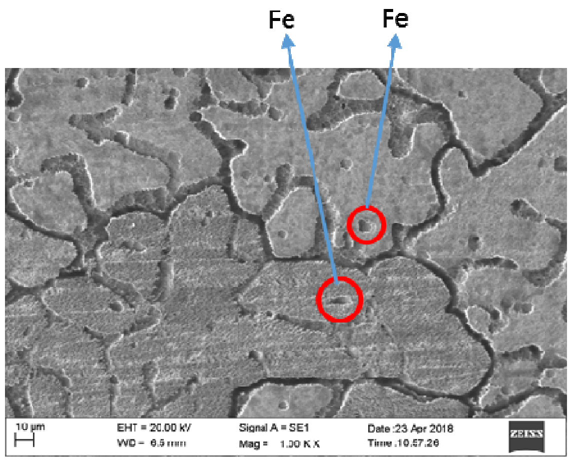

Figure 4.8: Cu-2% Steel as-Cast-1000X

Cu-2% Fe powder composite: In 2% Fe reinforced composite in as-cast, grains are more equiaxial (Figures. 4.7 & 4.8). Porosity seems to be less, dendrites are also less. Grain boundaries are finer compared to other 2 cases (pure copper & 1% Cu composite). In the deformed (rolled) condition (Figures. 4.9 & 4.10), grains seem to be elongated in the direction of working. Some grains seem to be twisted because of the elevated hardness & strength during working [23].

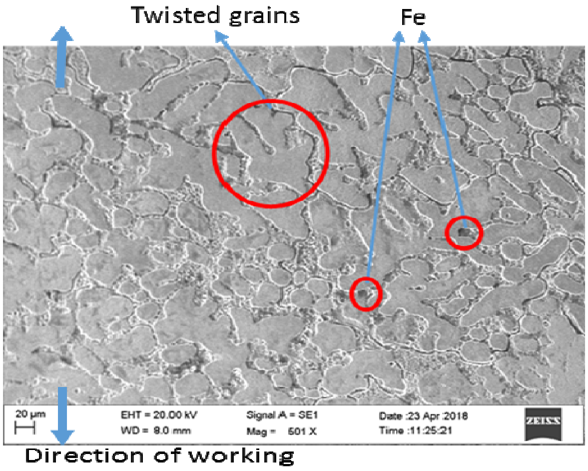

Figure 4.9: Cu-2% Steel 20%D-500X

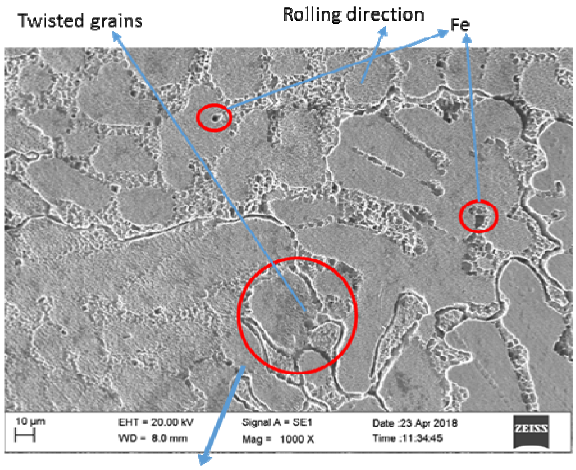

Figure 4.10: Cu-2% Steel 20%D-1000X

4.2 Hardness Test

The hardness of as cast pure copper is 88.5 BHN. As the wt. % of steel powder increases, hardness of copper composite increases. Accordingly, 1 & 2 wt.% steel powder show 92.3 and 105.7 BHN respectively (Figure.4.11). This is due to the increase in harder solid reinforcements into the lattice of copper. Also, the grains seem to be finer as the discrete nucleation sites (steel powder) for solidification increases [24]. Due to the addition of 2 wt.% reinforcement, hardness increases approximately by 20% compared to pure copper casting. As the degree of deformation increases, hardness of the pure metal and composite increases. In all 3 castings 50 to 60% increase in hardness is observed with 30% deformation as compared to respective as-cast specimens. This increase in hardness is attributed to the strain hardening of the matrix, wherein dislocation density and grain boundary density increases by cold working [23]. 1 wt.% reinforced copper composite is not so sensitive to deformation to increase the hardness values. This may be due to the negligible quality of reinforcement present in the matrix. As the cooling rate decreases, the hardness of the pure metal casting and composite decreases. This is clearly shown in Figure 4.12. Normalizing cooling rate is slower almost similar to as-cast, and annealed is still lower. Normalized and as-cast specimens show variation in hardness. The lesser hardness of normalized is due to the removal of dendritic segregation in normalizing [21-23]. Annealed & normalized both show almost closer hardness values in all 3 castings, but is far less than as-cast. The small variation in hardness value between annealed and normalized may be due to the weak driving force in transformative mechanism from larger grain to smaller grain, without phase transformation mechanism from high temperature to low temperature.

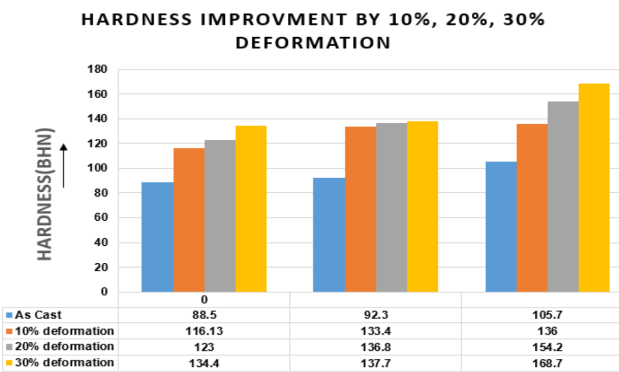

Figure 4.11: Hardness Improvement by 10, 20 and 30% Deformations

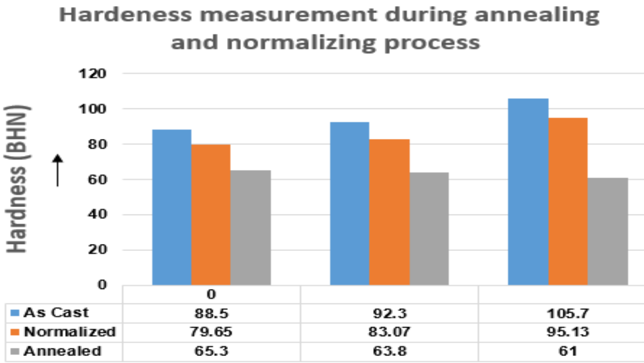

Figure 4.12: Hardness Measurement During Annealing and Normalizing Process

4.3 Tensile Test

Ultimate Tensile Strength (UTS): The UTS of normalized specimen is better than as-cast and is still better than annealed (Figure.4.13). The tensile strength of composite is better than the pure metal. As the wt. % of reinforcement increases, tensile strength increases. Annealed shows up to 10% reduction in UTS compared to as cast in all 3 cast specimens. Normalized shows 9% increase in UTS compared to as cast in respective cast samples. The 1 wt. % steel powder addition shows approximately 20% and 2 wt. % steel powder addition shows approximately 50% increase in UTS over that of pure copper. The increase in strength trend is slower compared to hardness increase trend as the wt. % of reinforcement increases. This may be due to the increase in porosity level in composites over pure metal. The porosities increase is higher with higher wt. % reinforcement addition in the composite. The typical stress-strain diagram in tensile load for pure metal is shown in figure 4.14.

The ductility in as-cast condition is less than normalized, but ductility of annealed is better than normalized & as-cast. As the wt. % of reinforcement increases in all conditions (heat treated & as-cast), the ductility of the casting decreases. This is due to the harder discrete reinforcement present in the matrix. The microstructure also supports the argument that annealed has larger grain and normalized & as-cast has finer grains. Finer the grain size, poor is the ductility [11]. This trend is seen clearly in the figure 4.15. Up to 66% reduction in ductility is observed in 2 wt. % reinforced composite compared to pure metal. Up to 40% increase in ductility is observed after annealing, when compared with respective as cast specimen.

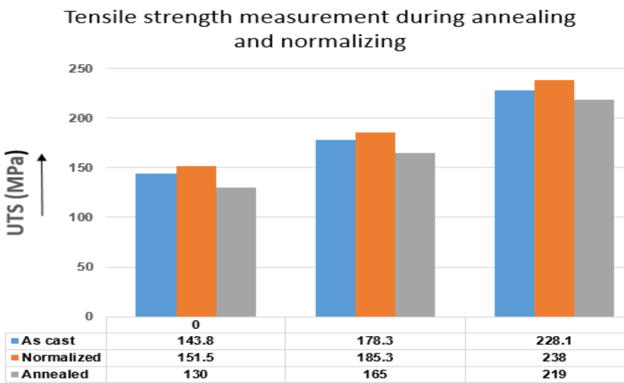

Figure 4.13: Tensile Strength Measurement During Annealing and Normalizing

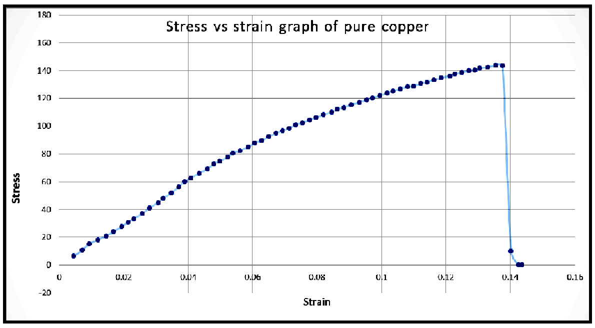

Figure 4.14: Stress vs Strain Plot for Pure Copper Under Tensile Load

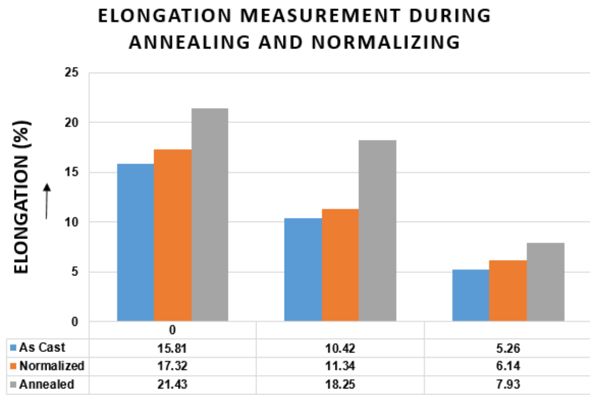

Figure 4.15: Elongation Measurement During Annealing and Normalizing

5. CONCLUSIONS

The copper– steel powder reinforced MMC is successfully cast by liquid stir casting process route. The castings are found to be sound without cracks and macro-porosities. The heat treatment is conducted to the reinforcement, which is embedded in the matrix successfully and deformed. The mechanical characterization is performed in deformed and heat treated conditions.

The following conclusions are drawn from present research study.

- In as-cast condition, the microstructure shows equiaxial grains with a lot of dendrites. The deformed (rolled) grains are elongated in the direction of working.
- Grain boundaries are finer in 2% steel powder reinforced compared composites, compared to pure copper and 1% steel powder composite.
- At the surface, some porosities are also observed. Subsurface grains in the casting appear to be finer compared to inner region.
- Annealed & normalized, both show almost closer hardness values in all 3 castings, but is far less than as-cast. In all 3 castings, 50 to 60% increase in hardness is observed with 30% deformation, as compared to respective as-cast specimens.

- The UTS of normalized specimen is better than as cast, and is still better than annealed. 58.6% increase in UTS value is observed for copper- steel powder composite in as-cast condition compared to pure copper.
- The ductility in as-cast condition is less than normalized, annealed is better than normalized & as-cast. As the wt. % of reinforcement increases in all conditions (heat treated & as cast), the ductility of the casting decreases.

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